

Conceptual development and simulation of a PLC-based greenhouse climate regulation system using synthetic data

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Abstract. This paper presents the conceptual design and simulation of an automated greenhouse climate control system aimed at melon cultivation in the coastal region of Ecuador. The proposal is based on the use of programmable logic controllers (PLC) and a human-machine interface (HMI), developed entirely within a simulation environment using synthetic data and predefined engineering assumptions. The system is designed to regulate critical environmental variables such as air temperature, relative humidity, and soil moisture through a structured and modular control logic implemented in Ladder language. The adopted methodology prioritizes logical and functional validation of the system without relying on physical sensors or field testing, allowing the evaluation of operational coherence under different simulated environmental scenarios. The results demonstrate stable and consistent system behavior, with appropriate automatic responses to conditions of thermal and water stress. Additionally, the proposed control strategy shows potential improvements in water use efficiency and greenhouse microclimate stability. This study represents a preliminary, non-experimental contribution that provides a structured foundation for future stages involving physical implementation, field validation, and the integration of advanced technologies in agro-industrial greenhouse automation systems.

Keywords: Greenhouse automation; Climate control; Programmable logic controller (PLC); Human-machine interface (HMI); System simulation.

1. INTRODUCTION

Controlled environment agriculture has gained relevance as a response to challenges such as climate variability, water scarcity, and the need to improve efficiency in food production systems. Greenhouse cultivation allows partial isolation from external conditions, enabling better regulation of internal variables that directly influence crop growth, yield stability, and product quality. However, in many agricultural contexts, greenhouse management continues to rely on manual practices based on empirical knowledge, often leading to inefficient use of water and energy, delayed responses to environmental changes, and inconsistent operational results (Venkataramanan et al., 2025).

In Ecuador, the coastal region extending from Esmeraldas to El Oro represents one of the country's most productive agricultural areas and offers favorable conditions for short cycle crops such as melon (*Cucumis melo*). Despite this potential, the adoption of automated greenhouse control systems remains limited due to economic constraints, restricted access to technology, and the lack of technical models adapted to local production conditions. Melon cultivation is highly sensitive to variations in temperature, relative humidity, and soil moisture, and the absence of systematic monitoring and control can negatively affect productivity and crop quality (Ardiansah et al., 2022).

From an engineering perspective, the conceptual design of greenhouse climate control systems based on programmable logic controllers and human machine interfaces provides a structured framework for evaluating automation strategies prior to physical implementation. Simulation tools allow analysis of control logic behavior and system interaction without relying on field measurements. Within this context, the use of synthetic data represents a practical alternative during early development stages. Accordingly, this study presents the conceptual design and simulation of a PLC based greenhouse climate control system using synthetic data as a preliminary reference for future agroindustrial applications (Alsayaydeh et al., 2023).

2. MATERIALS AND METHODS

The development of the proposed greenhouse climate control system followed a conceptual and technological design methodology focused on simulation and logical validation under industrial automation criteria. The study emphasized the functional behavior of the control strategy rather than experimental measurement or physical implementation, and all stages were developed using synthetic data and predefined engineering assumptions (Jaliyagoda et al., 2023).

The methodological process included the definition of system requirements, the conceptual selection of a programmable logic controller and a human machine interface compatible with industrial applications, and the structured design of control logic routines. These routines were implemented and evaluated within simulation environments compatible with Delta PLC programming platforms. No real sensors, field measurements, or on site testing were performed, clearly establishing the preliminary nature of the study (Huynh et al., 2023).

The control strategy was based on a set of critical environmental variables defined using general agronomic criteria and representative parameter ranges commonly applied in protected agriculture. Internal air temperature, relative humidity, and soil moisture were selected as the main variables due to their direct influence on crop development. Simulated operating ranges were established to evaluate system response under controlled conditions. Additionally, a day and night operating condition was included to differentiate control cycles and optimize simulated energy use (Ardiansah et al., 2024).

For the simulation, industrial automation components compatible with PLC based architecture were conceptually selected. The PLC was defined as the central processing unit, supported by analog input modules and a human machine interface for supervision and manual interaction. Environmental variables were modeled using synthetic input signals, while actuators such as irrigation and ventilation systems were represented as logical outputs activated according to predefined control conditions. Table 1 summarizes the main components and their functional role within the simulated architecture (Ardiansah et al., 2024) (Mishra et al., 2025).

Table 1 Main components used in the simulation of the automated greenhouse system

Component	Technical Description	System Function
Delta PLC DVP-14SS2	8 digital inputs, 6 digital outputs, 24 VDC supply	Central unit for logic processing and system control
Analog Module DVP04AD	4 analog inputs (0–10 V)	Acquisition and reading of sensor signals

HMI Delta DOP-B07S411	7-inch touchscreen display	Real-time monitoring and manual system control
Temperature Sensor Pt100	Range: -50 to 200 °C, accuracy ±0.5 °C	Accurate measurement of internal ambient temperature
Soil Moisture Sensor	Capacitive type, 0–10 VDC / 4–20 mA output	Monitoring of substrate moisture level
Relative Humidity Sensor	Range: 0–100%, 0–10 VDC / 4–20 mA output	Measurement of ambient humidity in the greenhouse
Frequency Converter	Rated for 5 HP, input voltage 220 VAC	Speed regulation for the water pump motor
Water Pump (5 HP)	220 VAC, flow rate: 400 L/min, pressure: 50 Psi	Automated irrigation system activation
Axial Fan 220 VAC	Airflow: 500 m³/h	Ventilation system for temperature control

Source: own authorship (2025).

All components were configured within the programming and monitoring software to emulate system behavior under varying simulated environmental conditions. This configuration allowed the evaluation of logical consistency, response sequencing, and operational stability within a fully simulated environment (Carrasco Agraces, 2024; Săcăleanu et al., 2024).

2.1. PLC Control Program Development

The greenhouse automation system was programmed using the WPLSoft environment for Delta programmable logic controllers, enabling the creation and simulation of Ladder Diagram control routines under fully simulated conditions. The control program was organized into independent functional blocks, each responsible for a specific process variable, ensuring logical clarity and future scalability. All control actions were based on synthetic input values generated within the simulation environment (Maravić Čisar et al., 2025).

Temperature control activates ventilation when simulated values exceed an upper threshold and deactivates it at a lower limit using hysteresis to ensure stability. Humidity control applies a similar strategy to reduce oscillations, while irrigation control activates the pump based on simulated soil moisture or conductivity with a predefined cycle and delay. In addition, a proportional–integral–derivative (PID) control strategy was implemented to regulate the frequency converter of the main actuators. Figure 1 presents the ladder diagram segment corresponding to the PID logic, which enables smooth regulation and improves energy efficiency and operational stability (Belovski et al., 2025; Carrasco Agraces, 2024).

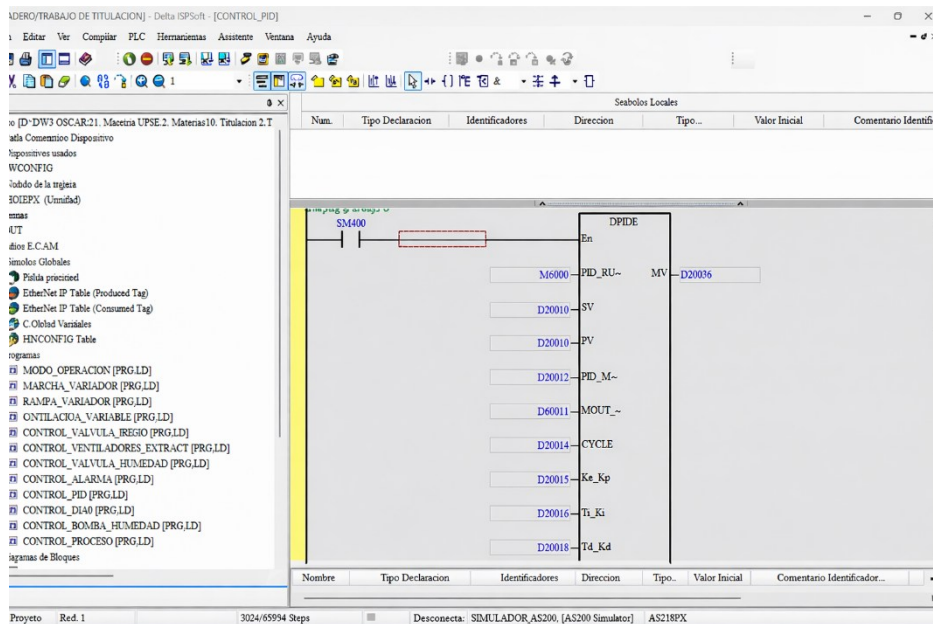


Figure 1. PLC PID control logic for frequency converter regulation

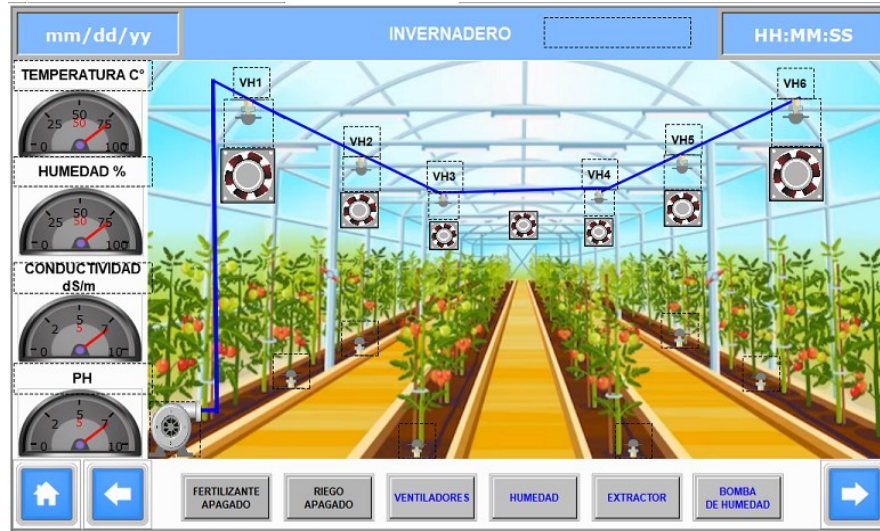


Figure 3. Main greenhouse overview screen

In addition to supervision, the HMI includes a dedicated configuration screen that allows dynamic adjustment of upper and lower control limits for process variables such as temperature, relative humidity, electrical conductivity, and pH. As shown in Figure 4, this interface enables the operator to modify setpoints directly from the HMI without altering the PLC program, providing flexibility and adaptability to different operating conditions or crop requirements.



Figure 4. Parameter configuration screen

Based on the simulated inputs and configured parameters, the PLC generated output signals that activated or deactivated actuators represented within the HMI interface, including irrigation systems, ventilation equipment, and humidification devices. Figure 5 illustrates the irrigation control screen, which allows the selection between manual and automatic operation modes. The interface supports two irrigation strategies: a scheduled irrigation method based on daily calendars and weekly frequency, and an automatic method driven by soil conductivity measurements.

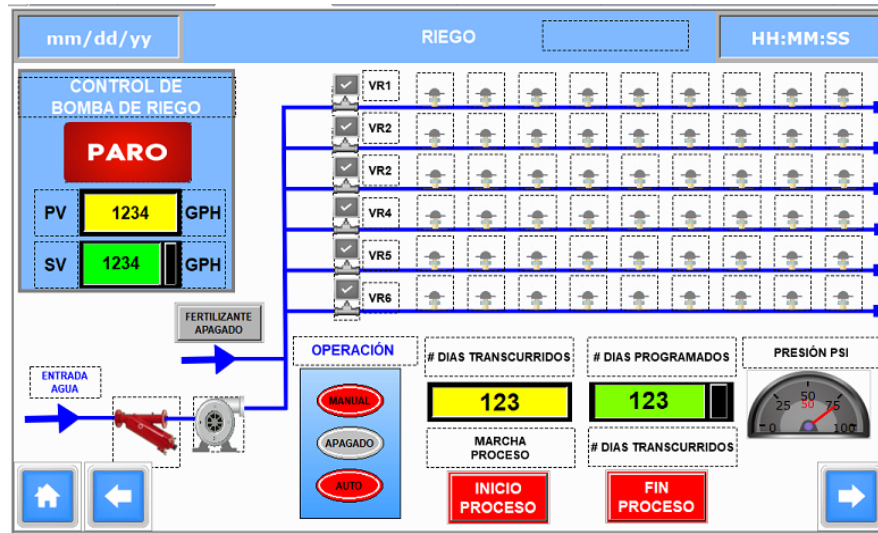


Figure 5. Irrigation control screen.

Several operating scenarios were defined to simulate contrasting environmental conditions, such as high daytime temperatures, increased nighttime humidity, and soil water deficit. The system response observed through the HMI under these scenarios confirmed the logical coherence, operational stability, and adaptive capability of the automated control strategy within a fully simulated environment (Ezurike et al., 2025).

2.3. Simulation of the Automated System

The validation of the automated greenhouse climate control system was carried out exclusively through simulation using EasySimulator, a software tool compatible with Delta PLC and HMI development environments. This approach made it possible to evaluate system behavior without the use of physical sensors or field installations, ensuring a controlled and reproducible framework for verifying the proposed control strategy. (Pizzileo et al., 2025)

During the simulation stage, synthetic analog input signals were generated to represent typical greenhouse environmental conditions, including variations in internal temperature, relative humidity, and soil moisture. These values were processed by the programmable logic controller according to the predefined control logic. Based on the evaluated conditions, the PLC generated digital output signals that activated or deactivated simulated actuators displayed in the HMI interface, such as ventilation systems, irrigation pumps, and misting devices. This configuration allowed verification of logical sequencing, coordination between control blocks, and overall system stability, while avoiding uncertainties associated with real sensor noise. (García-Chica et al., 2025)

Three representative operating scenarios were defined to assess system performance under contrasting environmental conditions. The corresponding input values and expected system responses are summarized in Table 2.

Table 2. Defined Operating Scenarios with Environmental Conditions and System Responses

Scenario	Environmental Conditions	Expected System Response
1	High temperature (>35 °C), normal humidity, dry soil	Activation of ventilation and irrigation to reduce temperature and moisten dry soil
2	Optimal temperature (~25 °C), low humidity (<50%), high soil moisture	Activation of the misting system to increase relative humidity without activating irrigation
3	Low temperature (<20 °C), other variables normal	System remains inactive to avoid unnecessary resource consumption

Source: own authorship (2025).

The simulation results demonstrated that the automated greenhouse control system responded consistently and reliably under all evaluated scenarios, without logical conflicts or programming errors. When simulated environmental variables exceeded or returned to predefined thresholds, the control routines operated as intended, confirming correct interaction between synthetic inputs, PLC logic, and simulated actuators. In scenarios combining high temperature and low soil moisture, ventilation and irrigation functions were activated simultaneously, verifying proper coordination between multiple control blocks (Rodríguez-Nieto et al., 2025).

The human-machine interface proved effective for system supervision and interaction, enabling real time visualization of process variables and actuator states, as well as controlled manual intervention when required. The simulated alarm system correctly identified abnormal conditions and registered events. Overall, the simulation confirmed the logical coherence and operational feasibility of the proposed control system, establishing a solid preliminary basis for future physical implementation and field validation (Benique et al., 2025).

2.4. Technical Considerations and Limitations

The proposed greenhouse automation system was developed entirely within a simulated environment, although all components correspond to commercially available industrial devices commonly used in agricultural automation. The control architecture was defined assuming standard industrial conditions, including 24 VDC control circuits and 220 VAC power supply, facilitating potential adaptation to real implementation scenarios (Albuja-Illescas et al., 2025).

The control logic and system structure were designed to be transferable to physical installations with minimal modifications, provided that equivalent hardware and proper calibration are applied. However, the use of synthetic data represents a limitation, as it does not capture real world variability, sensor noise, or unexpected disturbances present in actual greenhouse environments (Edan et al., 2023).

Another limitation is the lack of integration with Internet of Things platforms or cloud-based data storage, which restricts remote monitoring and long-term data analysis. These features may be incorporated in future development stages. Despite these limitations, the system fulfills its role as a conceptual and simulated model, providing a solid foundation for future implementation and field validation (Hooshmand, 2025).

3. RESULTS AND DISCUSSION

3.1. General Results of the Simulation

The validation of the automated greenhouse climate control system was performed through the simulation of multiple environmental scenarios designed to evaluate PLC response and overall system behavior. Synthetic sensor inputs were used to represent critical environmental variables, including internal temperature, relative humidity, and soil moisture. Based on these inputs, the system automatically activated or deactivated the corresponding actuators, such as ventilation fans, irrigation pumps, and humidification devices, in accordance with the predefined control thresholds.

The simulation results showed a high level of operational stability. In all evaluated scenarios, the system behavior remained consistent with the programmed control logic. Transitions between operating states occurred correctly, without delays, logical conflicts, or unexpected interactions between control blocks. The human machine interface provided accurate real time visualization of system variables and actuator status, supporting effective supervision during simulation.

These results confirm that the proposed control architecture is logically coherent and functionally robust within a simulated environment. Although the validation was not conducted under real field conditions, the observed system performance demonstrates that the design meets the defined technical objectives and provides a reliable foundation for future physical implementation and experimental validation.

3.2. Comparative Analysis: Manual vs. Automated System

To evaluate the technical contribution of the proposed automation strategy, a comparative analysis was conducted between a conventional manual operation model and the automated control system developed in this study. The comparison focused on key performance aspects relevant to greenhouse operation, including irrigation efficiency, precision in environmental control, resource utilization, level of human intervention, response time to environmental changes, and stability of the internal microclimate.

In manual operation models, environmental adjustments depend primarily on operator perception and experience, which can result in delayed responses and variability in control actions. This approach often leads to inefficient water usage, inconsistent environmental conditions, and increased labor requirements. In contrast, the

automated system responds immediately to changes in simulated environmental variables, applying consistent control actions based on predefined logic and thresholds.

The automated system demonstrated superior precision and repeatability in maintaining environmental conditions within desired ranges. Resource usage, particularly water and energy, was optimized through demand-based control strategies, reducing unnecessary actuator operation. Additionally, the reduction in manual intervention contributes to improved operational consistency and minimizes the risk of human error.

The comparative results summarized in Table 3 highlight the advantages of automation in achieving stable greenhouse microclimate conditions, improving system responsiveness, and supporting more efficient and sustainable agricultural operations. These findings reinforce the relevance of PLC based automation as a practical solution for greenhouse management under controlled and simulated conditions.

Table 3. Comparison between manual and automated control in melon greenhouses

Evaluated Criterion	Manual Control	Automated Control (PLC + HMI)	Estimated Improvement
Irrigation frequency	Once per day (fixed)	Sensor-based activation (moisture <35%)	30–35% water reduction
Temperature control accuracy	Visual estimation	DHT22 sensor ± 0.5 °C	Higher thermal precision
Relative humidity control	Not managed	Automatic control (misting system)	Microclimate stabilization
Water resource usage	High (no prior diagnosis)	Low (demand-based)	Water-saving
Human intervention	High (constant operator presence)	Low (HMI-based monitoring)	Labor reduction
Response capacity	Slow (operator-dependent)	Immediate (programmed response)	Operational efficiency

Source: own authorship (2025).

3.3. Impact on Agricultural Productivity and Sustainability

The impact of automation on melon cultivation was analyzed from a technical and sustainability oriented perspective based on simulated operating conditions. The automated control of temperature, humidity, and irrigation contributes to reducing response time and minimizing human intervention, which are key factors in improving operational consistency within greenhouse environments.

By maintaining environmental variables within predefined optimal ranges, the system reduces exposure to thermal and water stress conditions that negatively affect plant development. This controlled environment supports more stable crop growth and contributes to lower risk of disease development associated with unfavorable humidity and temperature levels. As a result, the automation strategy promotes improved crop health and operational reliability.

Based on simulated scenarios and reference agronomic assumptions, the proposed system shows the potential to increase melon yield within an estimated range of 20 to 30 percent. Additionally, demand-based irrigation control contributes to a projected reduction in water consumption of approximately 35 percent. The improved environmental stability may also lead to a decrease in the use of phytosanitary products within an estimated range of 15 to 20 percent. These values represent indicative estimates derived from simulation and are intended to support comparative analysis rather than to replace field validation.

Overall, the results suggest that automated greenhouse control systems can positively influence productivity and sustainability when applied under controlled conditions, providing a basis for future experimental evaluation.

3.4. Evaluation of Simulated Environmental Scenarios

To evaluate the operational behavior and robustness of the automated greenhouse climate control system, four simulated environmental scenarios were defined by combining different levels of internal air temperature, relative humidity, and soil moisture. These scenarios were selected to represent typical and contrasting operating conditions that may occur throughout greenhouse crop production cycles, including periods of thermal stress, water deficit, and favorable growing environments.

Each scenario was introduced into the system using synthetic analog input signals assigned to the programmable logic controller. These signals represented continuous environmental measurements and were processed by the PLC in real time according to the predefined control logic implemented in the system. Based on the evaluated conditions, Ramírez-Baquerizo, et al. (2025)

the controller generated digital output signals that activated or deactivated the corresponding actuators, including ventilation fans, irrigation pumps, and humidification systems. This process allowed the assessment of the system's capacity to respond dynamically to changing environmental conditions.

The human-machine interface played a central role during the simulation process by enabling continuous monitoring of all process variables and actuator states. Through the HMI, it was possible to verify in real time each control action executed by the PLC, observe transitions between operating modes, and evaluate the logical sequencing of responses. This visual supervision facilitated the detection of potential inconsistencies and confirmed the stability of system operation.

The evaluation of these scenarios demonstrated consistent and coherent system behavior, with control actions executed in accordance with the established thresholds and priorities. The specific environmental conditions applied in each scenario and their corresponding system responses are summarized in Table 4, providing a structured overview of the system's performance under simulated operating conditions.

Table 4. System behavior under different simulated environmental scenarios

Simulated Scenario	Critical Variable	Simulated Value	System Response	Activation Time
Hot and dry day	Temp. > 35 °C, humidity <35%	37 °C / 30%	Fan and irrigation pump activated	< 2 seconds
Humid night	Temp. 22 °C, humidity >85%	22 °C / 90%	All actuators turned off	—
Low humidity, optimal temp.	RH <50%, temperature 25–30 °C	45% / 28 °C	Misting system activated	< 3 seconds
Stable environment	All variables in optimal range	28 °C / 70% / 40%	System on standby mode	—

Source: own authorship (2025).

3.5. Graphical Representation of Results

The graphical analysis presented in Figures 6 and 7 provides a clear and quantitative comparison between conventional manual control practices and the proposed automated greenhouse control system, focusing on water consumption and internal temperature regulation. These graphical representations allow a direct visualization of the operational differences between both approaches and highlight the contribution of automation to resource optimization and microclimate stability, which are key factors for improving agricultural productivity and sustainability.

Figure 6 presents the estimated monthly water consumption for irrigation under two control strategies: manual operation and automated control. The values were obtained from simulated operating conditions based on predefined irrigation logic and reference agronomic assumptions. In the manual control scenario, irrigation follows fixed schedules or operator judgment, resulting in an estimated consumption of approximately 18000 liters per month. In contrast, the automated irrigation system activates only when simulated soil moisture values fall below the established threshold, reducing unnecessary water application.

As a result, the automated system shows an estimated monthly water consumption of approximately 11700 liters, which represents a reduction of about 35 percent compared to manual irrigation. This decrease illustrates the effectiveness of demand-based irrigation control in minimizing water waste and improving overall resource efficiency within a simulated greenhouse environment.

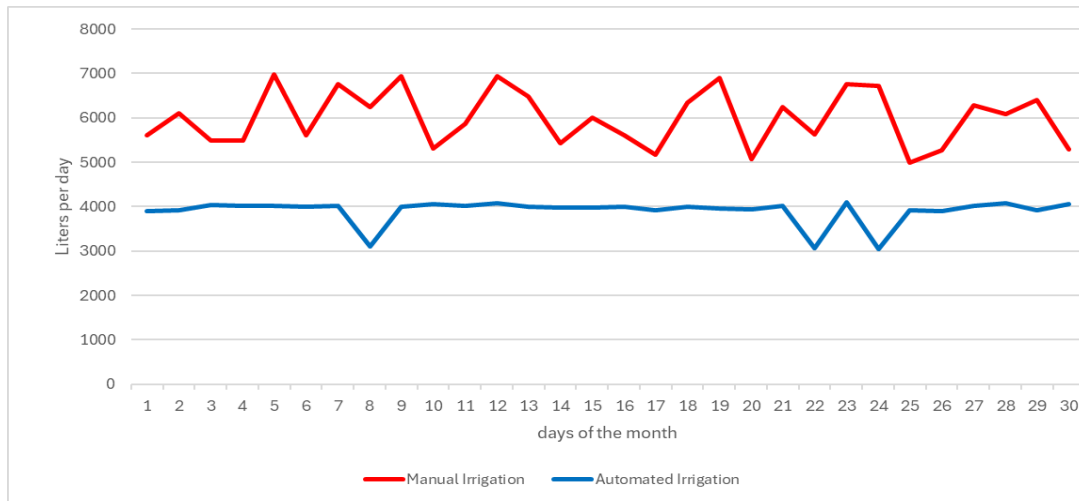


Figure 6. Estimated monthly water consumption for irrigation by control type.

This reduction is primarily attributed to the system’s ability to activate irrigation only when simulated soil moisture values fall below predefined thresholds, thereby preventing over irrigation and unnecessary water use. These projected savings not only contribute to the conservation of water resources but also represent potential economic benefits for producers by reducing operating costs. In the context of increasing water scarcity and the need for sustainable agricultural practices, efficient irrigation management becomes a critical factor for long term production viability under greenhouse conditions.

Precise irrigation control also has a direct influence on crop health and development. By avoiding excessive soil moisture, the automated system reduces the risk of root related diseases and nutrient leaching, which supports more stable plant growth. Additionally, demand-based irrigation aligns water application with the crop’s phenological requirements, supplying water according to simulated plant needs rather than fixed schedules. This approach promotes more consistent growing conditions and improves overall system efficiency.

Figure 7 presents a comparison of internal greenhouse temperature variations over an equivalent simulated period, contrasting manual environmental control with automated regulation. Under manual control conditions, temperature values exhibited wider fluctuations, with oscillations of approximately plus or minus seven degrees Celsius. Such variations can generate thermal stress in plants, potentially affecting key physiological processes such as photosynthesis, transpiration, and flowering. In contrast, the automated system-maintained temperature within a narrower operating range, demonstrating improved stability under simulated conditions.

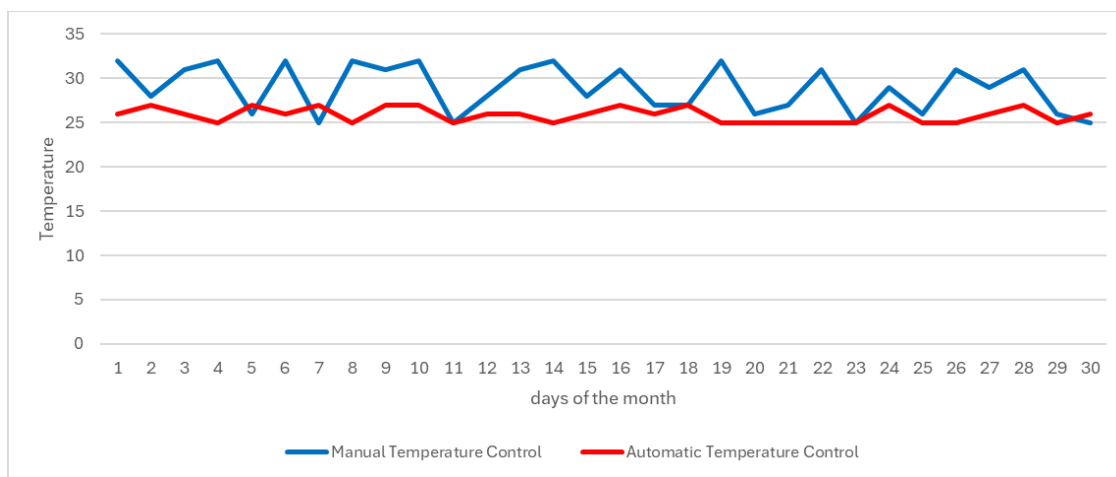


Figure 7. Temperature variation in the greenhouse with and without automated control

In contrast, the automated control system maintained the internal greenhouse temperature within a significantly narrower range of approximately plus or minus two degrees Celsius. This level of thermal stability was achieved through the integration of synthetic sensor inputs with the programmed activation of ventilation systems and shading mechanisms, all coordinated by the programmable logic controller. Maintaining a stable internal temperature helps protect crops from extreme thermal conditions, reduces plant stress, and supports more uniform growth, which may contribute to improvements in both yield quality and production consistency under simulated conditions.

The improved environmental regulation demonstrates the system's capacity to respond dynamically to changing external influences such as variations in ambient temperature, humidity, and simulated solar radiation. By continuously monitoring these variables and adjusting actuator operation accordingly, the automated system illustrates the advantages of real time feedback control compared to periodic manual intervention. From an agronomic perspective, this results in a more resilient growing environment that supports stable plant development despite external variability.

Taken together, the graphical results emphasize the effectiveness of the proposed greenhouse automation system in optimizing resource use and maintaining favorable growth conditions. By ensuring controlled irrigation without excess and stabilizing internal temperature levels, the system supports sustainable agricultural practices with potential environmental and economic benefits. These findings confirm the technical viability of the proposed solution within a simulated framework and support its consideration for future implementation and evaluation in precision agriculture applications.

3.6. Technical Discussion: PLC and HMI Performance

The Delta DVP 14SS2 programmable logic controller demonstrated adequate performance for managing the analog and digital inputs and outputs required in the simulated greenhouse climate control system. Its compact design and modular structure support the integration of additional sensors or actuators in future development stages. The use of Ladder Diagram programming facilitated logical verification, troubleshooting, and comprehension of the control routines, making the system accessible not only to automation specialists but also to technicians and engineering students.

The Delta DOP B07S411 human machine interface provided an effective solution for system supervision and operator interaction. Through a set of structured and intuitive screens, users were able to monitor simulated environmental variables, verify actuator status, and execute manual control actions when required. The interface allowed real time visualization of system behavior without the need to access the PLC programming environment, improving operational clarity and usability within the simulated framework.

3.7. Identified Limitations and Future Projections

The main limitations of the proposed system are related to its conceptual and simulated nature. It does not incorporate Internet of Things platforms or supervisory control systems, which limits remote monitoring and long-term data storage. Additionally, the absence of backup power solutions represents a vulnerability during electrical outages, and the system excludes complementary sensors such as carbon dioxide, solar radiation, and atmospheric pressure. Future work may address these limitations by integrating wireless communication, cloud-based data management, backup energy systems, and additional sensors, as well as validating the system under real field conditions and larger scale installations.

3.8. Academic Value and Technology Transfer Potential

The proposed automated greenhouse control system represents a valuable educational and applied engineering tool for agricultural contexts in Ecuador. Its design integrates principles of industrial automation, electronics, control programming, and agronomic management, promoting interdisciplinary learning and practical skill development. From a technology transfer perspective, the use of commercially available components and standard industrial architecture supports feasible adoption without the need for complex infrastructure or specialized resources.

The conceptual and modular nature of the system facilitates its adaptation to different educational, research, and productive environments. As a result, the project contributes both to academic training and to the promotion of technological innovation in agricultural automation, particularly in regions seeking sustainable and accessible solutions for modern farming challenges.

3.9. Economic Evaluation and Return on Investment (ROI)

Within the context of applied industrial sciences, the technical feasibility of an automated system must be supported by an economic assessment. For this reason, a preliminary economic evaluation was conducted to estimate

the initial investment and potential return on investment of the proposed greenhouse automation system, based on simulated operating conditions and reference prices typical of the Ecuadorian market.

The estimated initial investment includes the programmable logic controller, human machine interface, sensors, actuators, electrical infrastructure, and basic installation labor. Based on typical local prices, the total investment is estimated between 9000 and 15000 United States dollars, depending on greenhouse size, equipment quality, and system robustness. This estimate assumes the use of commercially available industrial grade components equivalent to those modeled in the simulation.

Operational savings were derived from simulated performance, indicating an approximate 35 percent reduction in water consumption and a decrease in labor requirements due to automation. Using a simplified approach, the estimated payback period ranges between 3 and 5 years. Although preliminary and simulation based, these results suggest that PLC and HMI based greenhouse automation is an economically reasonable option for improving efficiency and sustainability in agricultural production.

CONCLUSIONS

The conceptual development and simulation of an automated greenhouse climate control system for melon cultivation demonstrated the feasibility of applying industrial automation technologies to agricultural production systems in the coastal region of Ecuador. Using a programmable logic controller and a human machine interface, a structured control strategy was defined to regulate critical agroclimatic variables such as temperature, relative air humidity, and soil moisture, which directly influence crop performance and plant health.

The simulation results confirmed the correct logical operation of the system under multiple predefined environmental scenarios. The automated control routines responded in a consistent and timely manner according to the programmed thresholds, validating the functional coherence of the control architecture within a simulated environment. Additionally, the analysis indicated improvements in operational efficiency, including an estimated reduction in water consumption of approximately 35 percent and a decrease in the level of human intervention required. These results suggest that greenhouse automation represents a technically viable and potentially cost-effective alternative for small and medium scale agricultural producers when evaluated under controlled assumptions.

Compared to traditional manual management practices, the automated system exhibited advantages in terms of precision, stability of the internal microclimate, and reduction of operational variability. The modular design of the proposed solution allows scalability to larger greenhouse installations, adaptation to different crop types, and the incorporation of additional control functions as needed. Furthermore, the system architecture supports future integration with advanced technologies such as remote monitoring platforms and supervisory control systems.

From an academic and training perspective, this work contributes to bridging theoretical concepts and applied engineering practice. The proposed system can be used as a reference model in educational environments to strengthen competencies in industrial automation, control systems, and agro-industrial applications.

In summary, the automation of greenhouse climate control using PLC and HMI technologies constitutes an effective and replicable approach with significant potential to support sustainable agricultural production. This study establishes a preliminary foundation for future implementation, field validation, and technological expansion aimed at addressing productivity, environmental, and resource management challenges in modern agriculture.

REFERENCES

- Albuja-Illescas, L. M., Gómez-Cabezas, M., Jácome-Aguirre, G., Aragón-Suárez, J. P., Jiménez-Lao, R., Peña-Fernández, A., & Lao, M. T. (2025). Microclimate Characterization of a Low-Tech Greenhouse During a Tomato Crop (*Solanum lycopersicum* L.) Production Cycle in Chaltura, Imbabura. *Plants*, 14(23). <https://doi.org/10.3390/plants14233702>
- Alsayaydeh, J. A. J., Yusof, M. F., Hern, C. K., Ahmad, M. R., Shkarupylo, V., & Herawan, S. G. (2023). Greenhouse horticulture automation with crops protection by using Arduino. *International Journal of Advanced Computer Science and Applications*, 14(10). <https://doi.org/10.14569/IJACSA.2023.0141013>
- Ardiansah, I., Calibra, R. G., Bafdal, N., Bono, A., Suryadi, E., & Nurhasanah, S. (2022). An IoT-enabled design for real-time water quality monitoring and control of greenhouse irrigation systems. *INMATEH – Agricultural Engineering*, 68(3). <https://doi.org/10.35633/inmateh-69-39>
- Ardiansah, I., Nusantara, E. V., Putri, S. H., & Permana, R. H. (2024). A study on microclimate monitoring and control inside greenhouse using fans automation. *Indonesian Journal of Electrical Engineering and Computer Science*, 33(1), 101–112. <https://doi.org/10.11591/ijeecs.v33.i1.pp101-112>

- Attia, M., Belghar, N., Driss, Z., & Soltani, K. (2025). Automated Hydroponic System Measurement for Smart Greenhouses in Algeria. *Solar Energy and Sustainable Development Journal*, 14(1), 111–130. <https://doi.org/10.51646/jesed.v14i1.306>
- Belovski, I., Mihalev, T., Koleva, E., & Mandadzhiev, A. (2025). Arduino-Based Sensor System Prototype for Microclimate Monitoring of an Experimental Greenhouse. *Engineering Proceedings*, 104(1), 54. <https://doi.org/10.3390/engproc2025104054>
- Benique, M. A. R., Falcon Teves, L. E., & Vasquez Ortiz, E. A. (2025). Smart irrigation system with internet of things for rose cultivation in a basic greenhouse in Canchis, Cusco. *International Journal of Reconfigurable and Embedded Systems*, 14(3), 754–765. <https://doi.org/10.11591/ijres.v14.i3.pp754-765>
- Carrasco Agraces, O. O. (2024). Desarrollo de un sistema de automatización de un invernadero para cultivo de melones en el cantón Lomas de Sargentillo [Tesis de maestría, Universidad Estatal Península de Santa Elena]. Repositorio Institucional UPSE. <https://repositorio.upse.edu.ec/items/a812136b-e621-47ac-8bf9-0da28be50d2a>.
- Maravić Čisar, S., Stanić Molcer, P., & Pinter, R. (2025). Design and implementation of an IoT-based smart irrigation system for sustainable agriculture. *Acta Polytechnica Hungarica*, 22(12), 1–14. https://acta.uni-obuda.hu/MaravicCisar_StanicMolcer_Pinter_164.pdf
- Dudnyk, A., Pasichnyk, N., Yakymenko, I., Lendiel, T., Witaszek, K., Durczak, K., & Czekala, W. (2025). Smart Resource Management and Energy-Efficient Regimes for Greenhouse Vegetable Production. *Energies*, 18(17), 4690. <https://doi.org/10.3390/en18174690>
- Edan, Y., Adamides, G., & Oberti, R. (2023). Agriculture Automation. *Springer Handbooks of Automation: Vol. Part F674* (pp. 1055-1078). Springer Science and Business Media Deutschland GmbH. https://doi.org/10.1007/978-3-030-96729-1_49
- Ezurike, B. O., Ajah, S. A., Ijeh, I. C., Nwawelu, U. N., Chuks, C., Nwokenkwo, U., & Okoronkwo, C. A. (2025). Numerical modeling and thermal analysis of an energy-efficient smart greenhouse. *Energy Science & Engineering*. Advance online publication. <https://doi.org/10.1002/ese3.70248>
- García-Chica, A., Chica, R. M., Caparros-Mancera, J. J., Giménez-Fernández, A., & Torres-Moreno, J. L. (2025). Future of smart greenhouses in Almería: Farmers' perspectives and fuzzy logic-based evaluation. *Smart Agricultural Technology*, 12, 101515. <https://doi.org/10.1016/j.atech.2025.101515>
- Hooshmand, A. H. (2025). Smart modular greenhouse control via IoT, LabVIEW, and PSO-PID integration. *Computers and Electrical Engineering*, 128(Part B), 110713. <https://doi.org/10.1016/j.compeleceng.2025.110713>
- Huynh, H. X., Tran, L. N., & Duong-Trung, N. (2023). Smart greenhouse construction and irrigation control system for optimal Brassica juncea development. *PLOS ONE*, 18(10), e0292971. <https://doi.org/10.1371/journal.pone.0292971>
- Jaliyagoda, N., Lokuge, S., Gunathilake, P. M. P. C., Amaratunga, K. S. P., Weerakkody, W. A. P., Bandaranayake, P. C. G., & Bandaranayake, A. U. (2023). Internet of things (IoT) for smart agriculture: Assembling and assessment of a low-cost IoT system for polytunnels. *PLOS ONE*, 18(5), e0278440. <https://doi.org/10.1371/journal.pone.0278440>
- Mishra, R. K., Dash, A. R., & Panda, A. K. (2025). IoT-enabled smart farming: A cloud-based approach for polyhouse automation. *Expert Systems with Applications*, 279, 127358. <https://doi.org/10.1016/j.eswa.2025.127358>
- Naagarajan, R. A., & Streif, S. (2025). Enhancing greenhouse management with interpretable AI: A natural language interface for advanced and optimization-based control. *Smart Agricultural Technology*, 11, 101041. <https://doi.org/10.1016/j.atech.2025.101041>
- Pizzileo, G., Colizzi, L., Guerriero, E., Adamo, T., & Chiriaco, M. V. (2025). Resource use efficiency and environmental sustainability in greenhouse agriculture through IoT-based irrigation and fertilization management. *Smart Agricultural Technology*, 12, 101180. <https://doi.org/10.1016/j.atech.2025.101180>
- Rocamora-Osorio, C., Aragon-Rodriguez, F., Codes-Alcaraz, A. M., & Ferrández-Pastor, F.-J. (2025). Automated IoT-Based Monitoring of Industrial Hemp in Greenhouses Using Open-Source Systems and Computer Vision. *AgriEngineering*, 7(9), 272. <https://doi.org/10.3390/agriengineering7090272>
- Rodríguez-Nieto, D., Navas, E., & Fernández, R. (2025). Automated seeding in hydroponic greenhouse with a dual-arm robotic system. *IEEE Access*, 13, 1–14. <https://doi.org/10.1109/ACCESS.2025.3541954>
- Săcăleanu, D.-I., Matache, M.-G., Roșu, Ș.-G., Florea, B.-C., Manciu, I.-P., & Perişoară, L.-A. (2024). IoT-Enhanced Decision Support System for Real-Time Greenhouse Microclimate Monitoring and Control. *Technologies*, 12(11), 230. <https://doi.org/10.3390/technologies12110230>

- Traiphath, W., Nramat, W., Sukruan, P., Utaprom, P., Piamboriboon, P., & Naramat, S. (2025). Experiments comparing the efficiency between watering vegetable crops with traditional methods and automatic watering systems. *EUREKA: Physics and Engineering*, (1), 66-74. <https://doi.org/10.21303/2461-4262.2025.003657>
- Venkataramanan, V., Pimpale, M., Kapure, V., Mishra, P., Rokade, A., Bhushan, T., & Singh, J. (2025). A Hybrid IoT and Machine Learning Framework for Smart Greenhouse Automation in Sustainable Agriculture. *International Research Journal of Multidisciplinary Technovation*, 7(4), 58-69. <https://doi.org/10.54392/irjmt2545>